Preprint

Towards Freezing Global Warming

Neil Phillips[1*], Sarah M. Ayling[2], Norman M. Ratcliffe[3,4], Ben de Lacy Costello[3,4], William Foord[2], Thomas C. Draper[3], Anthony Plumridge[5] and Jona Razzaque[6]

ABSTRACT Numerous policies have been proposed to mitigate the problem of climate change as reducing emissions alone will not be sufficient. Carbon Capture and Storage (CCS), which captures carbon at the source, and Negative Emissions Technologies (NETs), which remove carbon from the atmosphere, are two of the most important strategies currently used to combat global warming. Existing technologies, however, are widely believed to be too expensive to implement on a global scale. The estimated total cost of climate change varies greatly, for example, \$178 trillion over the next 50 years. Economists have frequently emphasised the importance of minimising expenditure while meeting climate goals. According to new research, NETs may be more cost-effective and less disruptive than various forms of CCS. We anticipate that NETs based on plant growth and biomass freezing in seawater will be the most cost-effective option for capturing and storing 10 gigatonnes of carbon per year, with an operating cost in the order of \$50/t CO_2. To reverse global warming, policies at the national, transnational, and international levels will need to be overhauled.

Keywords Carbon capture · sequestration · composite ice · Antarctica · terraforming

1 INTRODUCTION

Our paper outlines the challenges of tackling global warming and proposes a novel solution that overcomes the financial barrier which prevents other proposals from being implemented. Following that, it provides a road map for reversing global warming as well as an update on the current state of project development. Finally, it focuses on the policy changes that will be necessary for full implementation.

Although the Earth's temperature fluctuates there is a clear trend of increasing temperature above pre-industrial levels over time (Guilyardi et al. 2018; Allen et al. 2019; IPCC 2021). Scientific evidence indicates that human activities have warmed the Earth's surface, which in turn has impacted the Earth's climate. The potential for human activities, such as burning fossil fuels, to raise atmospheric carbon dioxide levels and thus global temperatures was recognised as long ago as 1896 by Arrhenius (Arrhenius 1896) although he did not appreciate that there could be negative as well as positive effects of these changes.

---

1. College of Arts, Technology and Environment, University of the West of England, Bristol, UK
2. School of Geography and Environmental Management, University of the West of England, Bristol, UK
3. Institute of Bio-Sensing Technology, University of the West of England, Bristol, UK
4. Centre for Research in Biosciences, University of the West of England, Bristol, UK
5. School of Accounting and Finance, College of Business & Law, University of the West of England, Bristol, UK
6. Bristol Law School, College of Business and Law, University of the West of England, Bristol, UK

* Corresponding author: neil.phillips@uwe.ac.uk

The Intergovernmental Panel on Climate Change (IPCC), has stated that "Since systematic scientific assessments began in the 1970s, the influence of human activity on the warming of the climate system has evolved from theory to established fact." (IPCC, 2021; Arias et al. 2021). In July 2023 Antonio Guterres (UN General Secretary) stated “The era of global warming has ended; the era of global boiling has arrived. The air is unbreathable. The heat is unbearable, and the level of fossil-fuel profits and climate inaction is unacceptable. Leaders must lead. No more hesitancy. No more excuses. No more waiting for others to move first. There is simply no more time for that.” (United Nations, 2023a).

This statement was prompted by a series of record climate events, including global average temperatures of 17.2°C and Antarctic sea-ice extending 1.3 million sq. km below the previous lowest value (Met. Office 2023a and b). The impacts of climate change include both rising sea levels (Edwards et al. 2019) and more extreme weather events (Met. Office 2023b). As emphasised by UK Met. Office (Met. Office 2023c), even if all emissions of greenhouses gases stopped there will still be changes in the climate, but the sooner emissions are reduced the best chance humanity has of minimising the rate and extent of changes. The challenge is how to reduce emissions and slow or halt Global Warming without further disadvantaging those peoples who already lack access to the facilities considered vital for sustainable development (United Nations 2023b).

192 nations agreed, under the Kyoto Protocol of 1997, to limit emissions of greenhouse gases and established legally binding targets for 37 industrialised countries and the EU (United Nations no date a and b). The Paris Agreement of 2015, which came into force in 2016, replaced the Kyoto Protocol and adopted a decentralised approach in which nations establish their own emission reduction targets (United Nations, no date c). Under the Paris Agreement, targets were set to slow and limit global warming to 1.5 °C above pre-industrial era temperatures, but progress is not fast enough and without dramatic reductions in levels of atmospheric greenhouse gases, climate scientists think there is a fifty percent chance that by 2040 global warming will exceed 1.5 °C and reach 2.7 °C at the end of the century (UN Environment Programme (UNEP) 2020). The Paris Agreement is signed by 194 nations from the developed and developing world and establishes a financial mechanism aimed at delivering technical and capacity-building support to countries that exhibit heightened vulnerability to the consequences of climate change (United Nations no date c). In 2022, delegates at the COP27 talks agreed to create and put into action a loss and damage fund (United Nations, no date d). However, the idea of direct reparations is politically unpopular in some countries, especially following the economic impact of the Covid pandemic and Russian military operations in Ukraine. For example, in July 2023 the US special envoy on climate change, John Kerry, stated that the United States will not pay reparations to developing countries affected by climate-linked disasters (Reuters 2023).

Numerous ideas to combat global warming have been proposed (Biello 2007; Wildenborg et al. 2005). The foremost technologies can be divided into two groups as follows:

Carbon Capture and Storage (CCS) is the process of capturing or collecting carbon emissions from a significant source and then permanently storing them. For example, CCS from coal power stations and cement plants (Benson and Orr 2008; Hunt et al. 2010). Although the capacity of CCS is increasing (e.g., from 73 million tonnes in 2020 to 111 million tonnes in 2021) (G.C. Institute 2022), it is still too small to have a major impact on global warming. Carbon capture, utilisation, and storage (CCUS) is the process by which captured CO_2 is used, rather than stored, in other industrial processes or even in the manufacture of consumer goods. The primary processes employed for the capture of CO_2 include post-combustion, pre-combustion, and oxy-fuel combustion:

- **Post-combustion technology** involves the utilisation of a chemical solvent, among other methods, to separate CO_2 from the flue gas after the combustion of fuel (Chao et al. 2021).
- **Pre-combustion techniques** encompass the conversion of the fuel into a gaseous blend comprising primarily hydrogen and carbon dioxide. The high concentration of CO_2 is easier to separate away, yielding a gas which is rich in hydrogen and can be utilised as a fuel with no further emissions (Olabi et al. 2022).
- **Oxy-fuel technology** entails the combustion of a fuel using a high concentration of oxygen, resulting in the production of CO_2 and steam. The emitted CO_2 is subsequently captured for further utilisation or storage (Yadav and Mondal 2022).

Negative Emissions Technologies (NETs). Removal and sequestration of carbon dioxide from the atmosphere or enhancements of natural carbon sinks (National Academies of Sciences, Engineering, and Medicine 2019; Le Quéré et al. 2009). The primary NETs can be broadly classified into two categories: synthetic technologies (♦) and natural (∞).

♦ **Sorbent materials** are utilised to capture CO_2 from the ambient air, which is drawn over them by fans (Azarabadi and Lackner 2019; McQueen et al. 2021). Recently, a Lewis acid-base interaction–derived hybrid sorbent with polyamine-Cu(II) complex that captures over 220 grams of CO_2/kg (two to three times more than most direct air capture sorbents) has been reported (Chen et al. 2023).

♦ **Chemical adsorption** is a process that captures CO_2 molecules by passing air through a container containing an adsorbent material such as activated carbon or zeolite (Lu et al. 2008; Bezerra et al. 2011; Wang et al. 2021).

♦ **Liquids that react with CO_2 to form a solid compound**, such as monoethanolamine or potassium carbonate (Borhani et al. 2015; Oexmann et al. 2008; Grant et al. 2014).

♦ **Electrochemical reduction**, in which CO_2 is converted to carbon monoxide or other valuable chemical compounds (Sullivan et al. 2021; Moura de Salles Pupo and Kortlever, 2019; Renfrew et al. 2020).

♦ **Mineral carbonation**, a chemical reaction between CO_2 and metal oxides that results in stable carbonates (Snæbjörnsdóttir et al. 2020; Neeraj and Yadav 2020; Thonemann et al. 2022).

♦ **Regenerable solid-supported materials** for CO_2 capture from air, such as amine tethered sorbents, resin materials that undergo humidity swing, and solid sorbents with CO_2 capturing organic groups grafted on their surface (Varghese and Karanikolos 2020; Shi et al. 2020; Gelles et al. 2020).

∞ **Micro algae** sequestration, capture rate of 1.8 kg of CO_2 per kg of dry algal biomass formed (Baohua et al. 2020).

∞ **Bio-oil** sequestration involves converting waste biomass to bio-oil using processes such as fast pyrolysis, and then injecting the bio-oil into deep geological formations for permanent storage (Xiu and Shahbazi 2012).

∞ **Biochar**, produced by pyrolysis of biomass, has been estimated to have the potential to reduce CO_2 carbon equivalent emissions by up to 1.8 billion tonnes per year, via a combination of increasing carbon stored in soil and replacing use of fossil fuels (Woolf et al. 2010; Pant et al. 2023)

∞ **Wood burial** entails burying large amounts of organic material, such as wood biomass, in specific locations where they can slowly decompose over time while emitting CO_2 at a reduced rate (Zeng 2008).

Known technologies for carbon capture and storage are considered financially too expensive to be usable at a global scale (Baylin-Stern and Berghout 2021). The dilute atmospheric CO_2 concentration (~400 ppm) makes low cost, high-capacity, direct air CO_2 capture challenging (Sabatino et al. 2021). It is predicted that the cost of current and anticipated direct air capture technologies will be \$94 to \$232 per tonne within 10 years (Keith et al. 2018); this is still too expensive for global implementation. Estimates vary for the global cost, for example \$178 trillion over the next 50 years ("The turning point | Deloitte" 2022). Economists have consistently emphasised the importance of achieving climate goals at the lowest possible cost (Delbeke and Vis 2019). Recent analyses found that NETs may be less expensive and less disruptive than reducing some emissions at source (National Academies of Sciences, Engineering, and Medicine 2019). Photosynthesis by plants is the basis of many NETs; photosynthesis uses free, 'unlimited' energy from the sun to convert carbon dioxide in the atmosphere into stored carbohydrates. The UK government, amongst others, is encouraging landowners to plant trees and then to auction the 'credit' for the stored carbon on the carbon credits market (Forestry Commission 2023). Although the growing trees will capture carbon there does not appear to be a clear end use for the timber, and once the trees reach the end of their life they will begin to decay and release carbon. Other plant-based carbon capture schemes, such as bio-oil (Xiu and Shahbazi 2012) require energy-intensive steps to convert plant biomass into a more concentrated form of carbon, which can then be injected into suitable geological strata. Apart from the energy costs, it is unclear whether this will have any negative effects on aquifers. Growing trees, cutting them down, and burying them (returning the carbon extracted to the earth) is the most basic form of plant-based carbon capture (Zeng 2008). The Social Value of an Offset (SVO) for a finite time can have considerable value. For example, it has been reported that timber storage for 500 years has 95% of the value of permanent storage (Groom and Venmans 2023). The mass of carbon that plants can extract from the atmosphere and store depends on several factors including species, age, local environmental conditions and land-use type. Managed forests can store an average of ∼335t per ha., traditional agroforests an average of ∼145t per ha. and pastures an average of ∼46t per ha. (Kirby and Potvin 2007).

We hypothesised that preventing the carbon stored in timber from re-entering the atmosphere by storing it in frozen seawater is the most affordable way of 'breaking' the carbon cycle, see Figure 1.

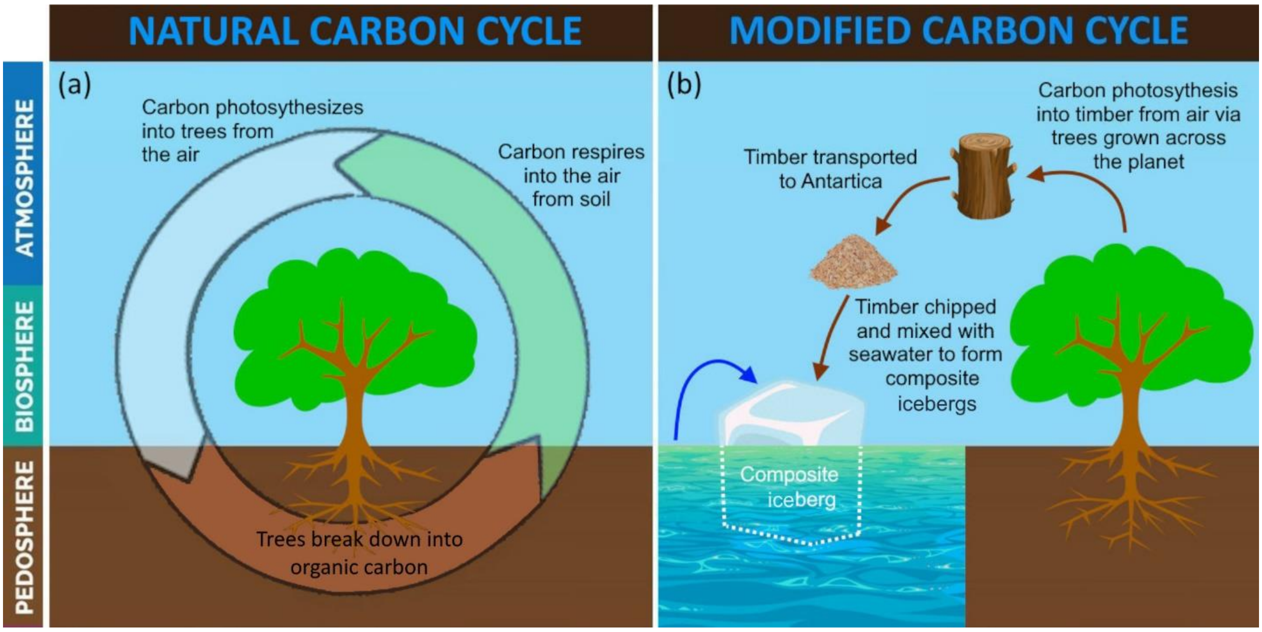

Figure 1: Graphical representation of carbon cycles (a) natural carbon cycle with net zero change (b) modified carbon cycle to reduce carbon release into atmosphere (source: authors).

Our novel solution combines three core principles and activities:

1. Cultivate as much biomass (specifically trees) as feasible, as photosynthesis represents the most cost-effective method for sequestering carbon from the atmosphere.
2. Ship the biomass (predominately timber) to suitable locations within the Antarctic Circle, where it is combined with seawater to create composite icebergs.
3. Transport composite icebergs to the Antarctic coast, where low temperatures prevent organic decay over geological timescales.

While there has been speculation regarding the storage of timber in Antarctica, such as the works of Holmes (2018) and Zeng (2008), to our knowledge no one has examined in detail how to implement the entire process, encompassing timber production and long-term storage on geological time scales. Additionally, we have successfully obtained Proof of Principle through an experimental testing programme that demonstrates a massive decrease of at least three-orders-of-magnitude in the rate of organic decay (Phillips et al. in preparation). The initial concept of amalgamating freshwater and wood chippings was formulated by Geoffrey Pyke in 1942 (Wikipedia 2022). Today, the eponymously named Pykrete continues to be employed for constructing structures in areas with cold climates (Hani and Evirgen 2022). Our research suggests that utilising seawater instead of freshwater for the formation of composite icebergs is a viable proposition. This is primarily due to the greater availability of seawater compared to freshwater, and our findings indicate that seawater exhibits enhanced efficacy in retarding organic decay. The utilisation of additive manufacturing enables the construction of 'functional' icebergs up to 400 m thick (utilising available ship building capability). This approach offers several advantages, including enhanced packing efficiency, improved durability of icebergs, and an ability to reflect sunlight back into space with snow-covered icebergs.

2 OBTAINING BIOMASS

Biomass can be obtained in many ways; each with different economic, social, and environmental impacts. It is essential that production of plant material to capture carbon does not damage sensitive ecosystems (arboreal or other) or compete with food production.

2.1 Establishment of new managed forests. Managed forests have the highest potential to extract carbon from the atmosphere, averaging -335t per ha. (Kirby and Potvin 2007). Only 7% of the 4 Bha. of forests worldwide are planted woodlands and plantations (World Resources Institute 2020). Creating new managed forests is a simple way to generate environmentally and economically viable timber. In countries, such as the UK, that promote afforestation to combat climate change and have a carbon credit trading system (Forestry Commission 2023) these policies could be expanded. Many existing tree planting schemes lack a clear end of life plan, particularly for the large volume of timber that will not be used for building construction or furniture manufacturing. Integration into composite icebergs would prevent this wood from decaying and thereby re-releasing the stored carbon. Tree planting at scale requires land use changes. In the UK, achieving net zero emissions by 2050 needs woodland coverage to increase from 13% to 17%. This expansion would require planting 1 million hectares of trees (Gambles 2019). Planting trees on degraded agricultural land can improve soil quality, water regulation, and ecosystem services (The World Bank 1991). Planting trees can protect established forests, link habitats, and increase biodiversity, but not as much as native forests (Wang et al. 2022). Strategic site selection will promote the positive environmental and social impacts of new woodland, and reduce the negative impacts associated with harvesting, processing and transporting timber. To deter exploitation of native and old-growth forests an effective and universally agreed monitoring system for timber production and provenance, with enforceable fines, is needed. At present timber supplied to sawmills exceeds reported timber production by 20%, and globally 60 million m^3 more timber is imported than exported (Fenning and Gershenzon 2002). Landowners will need a legally binding agreement for timber provision from new managed forests with protective measures to protect farmers in the event of project failure.

2.2 Fruit tree plantations. There are 37 billion fruit trees in 2.2 million orchards worldwide (Catlin et al. 2018). If all of these are replaced at the end of their lives, 333 billion trees of various species will need to be planted within 100 years. Although many fruit plantations are monocultures, there are financial pressures on major growers to promote biodiversity, reduce agrochemical use, reduce GHG emissions, and increase sustainability (EIT-Climate no date). Many orchards are already accessible by road or rail, so collecting timber would not necessitate the construction of additional roads.

2.3 Waste streams from existing timber production. The manufacture of wood products generates a significant amount of wood waste. Up to 80% of timber in Nigeria is lost during logging operations (Dionco-Adetayo 2001). Some timber waste is used for biomass power, which contributes to the use of renewable energy (Adhikari and Ozarska 2018). Because there is already infrastructure in place, such as sawmills, plantations, and roads, the cost (both environmental and financial) of collecting this material is lower than it would be from new plantations. However, creating a large market for waste timber may discourage efforts to improve the efficiency of timber harvesting and use, as well as putting additional pressure on natural forests.

2.4 Utilisation of Reclaimed Timber. Germany generated around 11.9 million tonnes of wood waste in 2015 (Adhikari and Ozarska 2018) which included wood packaging (21%), demolition and construction (26.7%), wood processing industry (14%), and municipal waste (20.7%). Some timber waste will have gone through extensive manufacturing and will require costly disassembly to extract the wood. Because the waste sources are dispersed, it is unlikely that they can be collected centrally. It would be preferable to reuse and repurpose these products locally, thereby reducing the emissions associated with their disposal. In the UK, 58.5% of waste wood was used as fuel in biomass burners in 2022, and 32% reused in other wood products (Wood Recyclers Association 2023).

2.5 Timber from private and public properties. Many people and businesses have trees on their properties that could contribute to the supply of timber. The financial cost and greenhouse gas emissions of harvesting individual or small groups of trees is a significant impediment to using this wood source. Government incentives could be used to encourage the harvesting of timber from parks and gardens, with the added benefit of encouraging urban tree planting. Increasing the number of trees in cities and suburbs has many benefits including reduced noise and visual pollution (Dwyer et al. 1991), reductions in the urban heat island, improved rainwater interception and biodiversity, and improved human mental health benefits (Woodland Trust 2023).

3 IMPLEMENTATION

3.1 Selecting land for new managed woodlands. Land on which new managed woodlands are created should be selected to cause the minimum negative impact and maximum positive impact. Areas of degraded farmland, areas of degraded woodland (particularly if adjacent to existing woodlands), and brownfield sites close to urban centres will all be considered. The knowledge held by local people can prevent the demolition of culturally or historically significant sites. Land surveys and resource studies can help identify crucial economic areas to avoid during planning. For the project to be successful, plantations must have access to seaports from which timber can be transported to the Antarctic. Any new roads should be positioned to create fire breaks within the woodland, thereby reducing the area lost from a potential wildfire. The location, scale and implementation of a tree plantation or managed woodland can affect socioeconomic well-being (Bayle 2019). Because they employ few people, tree plantations often have little direct socioeconomic impact. In sparsely populated areas managed woodlands can boost the local economy (Environment Agency 2002). Active involvement of local people in the planning process can maximise benefits while minimising negative economic and social issues.

3.2 Ecological impacts. Tree plantations, depending on factors such as type, management regime or location, have lower biodiversity than primary forests (Wang et al. 2022). Mixed plantations of native species have higher levels of biodiversity and provide more ecological benefits than monocultures of exotic species or intensive agricultural areas (Liu et al. 2018; Wang et al. 2022). While planted woodlands will never have the ecological diversity of natural forests, they can be sited to maximise biodiversity. Placed near natural forest edges and boundaries, planted woodland can buffer native forests and reduce the edge effect (Brockerhoff et al. 2008). Plantings can create wildlife corridors connecting primary forests and native ecosystems (Brockerhoff et al. 2008). Improved habitat links could help native species move and merge, improving gene flow and resilience (Correa Ayram et al. 2016).

3.3 Soil. Forestry can have a wide range of impacts on soil. Vehicles and heavy machinery used during site preparation and logging can cause soil erosion and compaction. Plantations, on the other hand, have the best soil stability of any type of agriculture (except natural forests) (The World Bank 1991; Smith et al. 2016). Natural forests have higher levels of soil nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium than tree plantations, and similar soil pH (Zarafshar et al. 2020). When compared to natural forests and tree plantations, agricultural soils generally have the lowest levels of soil nutrients, and establishing tree plantations in agricultural soil will likely increase nutritional content (Zarafshar et al. 2020). Natural forests have higher soil carbon levels (up to 36% higher) than tree plantations, which have 60% more soil carbon than agricultural land (Zarafshar et al. 2020). Planting trees on degraded agricultural land will increase soil carbon storage. The amount of carbon stored in soil is affected by the type of trees planted as well as the cultivation method (Danise et al. 2021). Different tree species have different nutrient requirements, but careful species selection and the use of mixed plantings can help to avoid nutrient depletion issues. For example, leguminous and nitrogen-demanding species complement each other well (Sharma et al. 2022). Planting in sympathy with the site and with appropriate mixed species will help to mitigate erosional issues. As a result, if the timber used in this project comes from managed woodlands, particularly if those woodlands are planted on degraded agricultural land, not only will carbon be stored in the timber, but soil carbon levels (as well as soil stability and fertility) will increase.

3.4 Method of tree cultivation. All agricultural rotation cycles and harvesting methods have significant impacts. Fast-growing trees with short rotation cycles can deplete soil nutrients (World Bank, 1991). When harvesting equipment is used in short rotations, it can compact the soil. Preference for specific nutrients can result in soil nutrient imbalances (World Bank 1991). Rotation lengths will be decided based on each species' annual carbon sequestration rate and published research (Kimberley et al. 2014; Zhou et al. 2017) to maximise carbon storage. The project will use a variety of trees and different rotation lengths to reduce any negative impact on soil nutrients and structure. Teak, for example, has a rotation length of 30-40 years compared to Neem (7-8 years); teak helps maintain soil structure while neem is harvested (Nanang et al. 1997). Coppicing can also help tree plantations survive and biodiversity thrive (Vanbeveren and Ceulemans 2019).

3.5 Felling trees. Clearing and log harvesting make plantations susceptible to soil erosion and instability. Removing vegetation can cause nutrient loss and increase leaching and soil disruption. No forest canopy will raise temperatures, killing soil organisms and drying the soil, making regeneration difficult. To reduce soil exposure, tree cover should be restored as soon as possible after clearing. The World Bank (1991) suggests mulching or planting faster-growing intermediate tree crops to protect exposed soils. Removal of forest cover reduces soil interception, infiltration, and water storage. Thus, rain-induced flash flooding and low flow can increase during dry months (The World Bank 1991; Okullo and Muhoro 2021). Suspended solids from increased water runoff and weakened soil structure can further disrupt waterways

(Shah et al. 2022). Debris from felling can block nearby watercourses, increasing flood risk, and causing eutrophication (Baillie 1996). Maintaining vegetation buffer zones around all waterways reduces runoff and sediment deposition (FAO no date; The World Bank 1991). Planning site preparation and harvesting for drier months will reduce flash flooding and soil instability; additionally, long downhill open extraction routes should be avoided, to reduce quick runoff (Shah et al. 2022). Debris can be checked regularly in waterways during harvesting to prevent blockages. Stream sediment traps can settle sediment in runoff-prone areas.

3.6 Transportation of timber. During the timber production life cycle, transportation is the primary source of greenhouse gas (GHG) emissions. Adhikari and Ozarska (2018) found that placing woodlands near waterways or the coast can reduce GHG emissions and other transportation impacts. River transport is one of the most GHG-efficient modes of transport available (EEA 2023) and should be used whenever possible. Globally the shipping industry is committed to reducing GHG emissions (CE Delft 2023) with major companies, such as Maersk aiming for net zero emissions by 2040 (Maersk 2022). Advances in the production of a new generation of wind-powered cargo ships (BBC 2023) will further reduce GHG emissions and improve transport efficiency. Whilst the primary concern regarding maritime transportation is the environmental impact, collisions with marine mammals (as well as noise and chemical pollution) are possible. Furthermore, in a variety of climates, ballast water has been identified as a potential source of invasive species. This danger can be reduced by cleaning and filtering ballast water at ports before returning it to the ocean. Ship arrival planning and distribution of timber across multiple ports can both help to reduce the risk of harbour ecosystem degradation.

3.7 Chipping timber. Sawmills have high energy and material requirements. GHG emissions can be reduced by using renewable energy sources such as hydroelectricity, wind power, and solar energy to power sawmills (Adhikari and Ozarska 2018). Alternatively, waste wood can be used in carbon-neutral biomass boilers. Ash and point-source CO_2 from biomass fuel can also be combined to produce construction products, further reducing CO_2 emissions (Tripathi et al. 2019).

3.8 Composite iceberg formation. When the ambient temperature is below the freezing point of seawater (−1.8 °C), composite icebergs can be formed by combining chipped timber and seawater (in liquid state). Within the Antarctic Circle is the most advantageous geographic location for this endeavour. The region surrounding the Antarctic Peninsula is sufficiently cold to freeze seawater for most of the year without the more extreme lower temperatures of Antarctic mainland. Sound and light pollution are potential issues due to the constant production of composite icebergs. Light pollution can disorient or blind bird species, causing collisions with ships (Cabrera-Criz et al. 2018), while sound pollution has been found to affect Antarctic wildlife (Sordello et al. 2020). This, combined with the constant cycle of ships dropping off timber, will make it one of the most active marine areas in the world, posing a risk to wildlife. As a result, detailed screening and planning are required to determine the best locations for iceberg production. This must be done in areas where the environmental impact is minimal. Composite icebergs can be made more wildlife-friendly by including a gradual slope that aids penguins to reach the top from sea level.

3.9 Positioning of composite icebergs. The majority of Antarctic wildlife can be found along its coastlines and relies heavily on these areas for food and migration. It is difficult to predetermine how the positioning of composite icebergs off the coast of Antarctica will affect penguin populations, but some predictions can be made based on current sea ice trends. The use of composite icebergs may initially have a positive impact on penguin populations. As a result of climate change and declining sea ice cover, many penguin species are losing their breeding habitat on thick sea ice (which they require for 9 months of the year) (ASOC 2022). Many emperor penguin colonies have been abandoned due to inconsistency in sea ice cover, so large icebergs of thick ice could be beneficial in mitigating population declines (ASOC 2022). However, these positive effects may change as the icebergs accumulate, as penguin populations can suffer if there is too much sea ice (Younger et al. 2015; ASOC 2022). Over time, monitoring (Fretwell et al. 2012) can be conducted to determine how the implementation of composite icebergs may affect penguin behaviour, and if negative impacts are found to be significant, specific areas important to penguin breeding should kept clear from composite icebergs.

3.10 Timeline. Figure 2 presents a project roadmap that demonstrates a positive outlook, encompassing essential activities, significant milestones, and anticipated deliverables. Proof of Principle has been achieved through an extensive period of experimental testing, the results of which will be shared in a forthcoming scientific publication (Phillips et al. in preparation). The scale demonstration is currently a Work-in-Progress (WIP), with discussions ongoing.

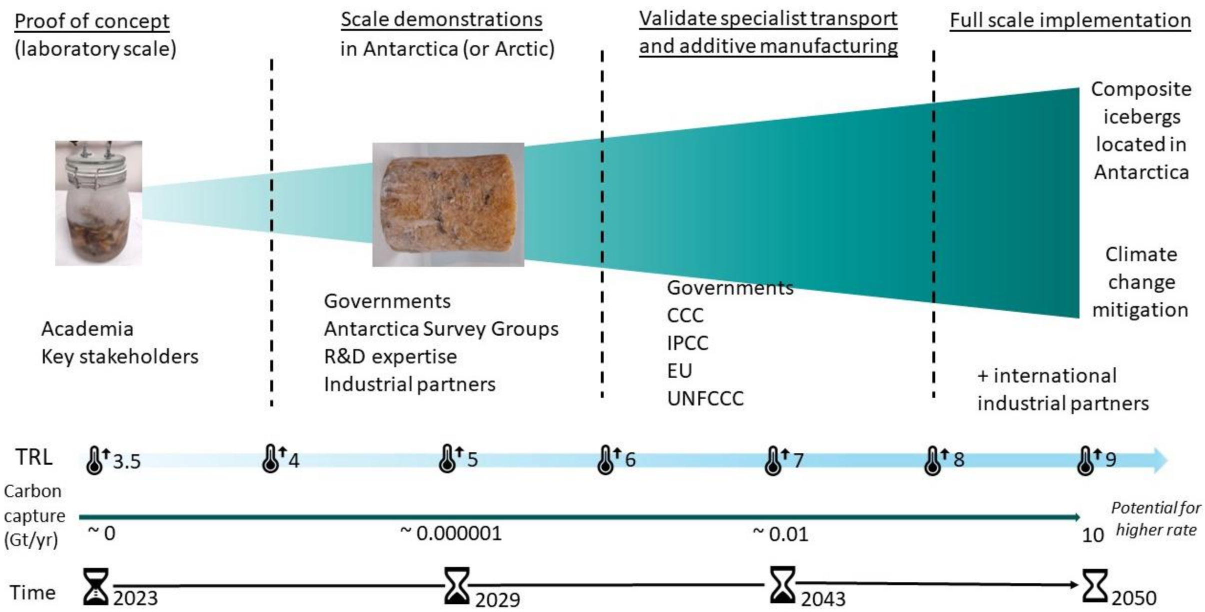

Figure 2: Graphical representation of project roadmap to assist stakeholders in recognising interdependencies and critical path to full implementation. The project is currently at Technology Readiness Level (TRL) 3.5 with Proof of Concept demonstrated in the laboratory (source: authors).

3.11 Financial cost of carbon capture. The preliminary assessment of operational expenses does not fully account for the project's entire life cycle, as certain costs, such as seaport depreciation, require additional investigation to accurately determine. The three major activities are as follows:

1. **Carbon removal from the atmosphere** via tree plantations has been considered in the range \$5 to \$100 per tonne of CO_2 (Austin et al. 2020). Which can be converted to \$18 to \$367 per tonne of carbon. Considering 10 gigatons (Gt) of carbon captured per year, an optimistic estimate of \$100 per tonne of carbon is suggested due to the large scale. Consequently, the total annual cost is projected to be around \$1000 billion.

2. **Composite berg formation** will require approx. 40 manufacturing cells (with freezing rate of ca. 1 m/hr). Each additive manufacturing cell contains four ships equipped with onboard bulk handling gear, reinforced hulls of approx. 500m length. A combined operating cost of \$40 billion per year.

3. **Transportation of biomass** can be divided into three legs:
   i) The transportation of biomass from plantations to chipping plants located on the Falkland Islands and/or southernmost part of South America. Approx. 46,000 cargo ships, each with a capacity of approx. 30 kt, incur an annual operating cost of approximately \$5 million per ship. Consequently, the total annual expenditure for operating these ships amounts to approx. \$650 billion.
   ii) Transportation of chipped biomass to manufacturing cells located in the vicinity of the Antarctic Peninsula. Around 5,000 shuttle cargo vessels, with reinforced hulls and 25 kt capacity. Annual operating cost ca. \$15 million (Solakivi et al. 2018) resulting in an estimated annual expenditure of approx. \$100 billion.
   iii) Relocating composite icebergs to the periphery of Antarctica. Approx. 250 icebreakers/tugboats, with an estimated annual operating cost of around \$100 million each, amount to a total expenditure of approx. \$50 billion per year.

The total operating cost is ~\$1840 billion per year, which can be expressed as ~<u>\$50 per tonne of carbon dioxide.</u>

The cost of carbon capture will vary depending on the efficiency of the shipping propulsion systems. Using current engines each cargo ship emits 5 g/t of CO_2 per km loaded and 1 g/t per km empty, assuming an average journey distance of ~8,000 km from the plantation to the Antarctic Circle. Each cargo ship emits ~1,440 tonnes of CO_2 on each round trip which requires an additional journey every 16 months to offset maritime transportation emission. Each round trip will take ~20 d assuming an average cargo ship speed of 15 kn when loaded and 22 kn when unloaded. Allowing for port time for loading, unloading, and vessel service/maintenance, this equates to approximately 15 return journeys per year. Overall, the project's efficiency is anticipated to further increase with the adoption of decarbonising technologies by the marine transport sector (BBC 2023).

3.12 Communication and dissemination. The primary goal is to effectively disseminate the project and its corresponding research outcomes to foster recognition and understanding among all stakeholders (including governments, the third sector, industry, academia, and people in general). The scope of the work needs to include the creation and implementation of visual identity and communication materials, as well as the coordination and execution of various events such as conferences, workshops, and community sessions. Additional resources (including publicly available computer-based simulations designed to model a variety of scenarios) should be employed to assist in public support of the project.

4 LEGAL POLICIES

To achieve full-scale implementation (which includes biomass production and transportation, as well as the fabrication and placement of composite icebergs), changes to legal policies at three distinct levels are required: national, transnational, and international.

4.1 National level. Most nations have demonstrated their dedication to engaging in afforestation and reforestation endeavours aimed at promoting timber production. The commitments outlined in this context are informed by the United Nations Framework Convention on Climate Change (1992), the Paris Agreement (2015), and the Convention on Biological Diversity (1992). Moreover, there exist non-binding objectives that provide guidance for afforestation and reforestation endeavours on a national scale, including the Bonn Challenge (2011), the New York Declaration on Forests (2014), the Sustainable Development Goals (2015), and the United Nations Strategic Plans for Forests 2030 (2019).

4.2 Transnational level. When biomass (predominately timber) is transported across national borders for the purpose of carbon capture, there are various transnational laws in place that govern the legality and sustainability of this activity. An example of a regulation that prohibits the introduction of unlawfully obtained timber and timber products into the European Union market is the EU Timber Regulation (2013). Australia, Japan, and the United States exhibit comparable instances of logging legislation.

4.3 Antarctica Treaty System. Antarctica encompasses designated regions that have been specifically safeguarded and regulated, resulting in their inaccessibility or imposition of particular restrictions. To gain access to specific regions, it may be necessary to obtain certain permits or specific authorization. An exemplification of this phenomenon is observable in the Antarctic Specially Protected Areas (ASPAs), which are characterised by the presence of officially designated management plans. Therefore, participation in activities within an ASPA requires the acquisition of additional permits and strict adherence to rigorous guidelines (Protocol on Environmental Protection to the Antarctic Treaty, 1991).

4.4 Research and planning. All proposed activities must undergo thorough environmental impact assessments to assess their potential environmental effects and ensure their alignment with conservation goals and guidelines.

4.5 Exploratory evaluation. Compliance with regulations, adherence to best practises, and the prompt implementation of corrective actions are critical. All activities must adhere to the Protocol on Environmental Protection, specifically Annex VI. Transportation, lodging, waste management, safety protocols, emergency response, and health requirements must all be implemented appropriately.

5 FURTHER CONSIDERATIONS

Global Warming poses an existential threat to the biosphere. Halting and reversing climate change will require a decrease in overall net emissions, and implementation of methods to remove and capture carbon dioxide (and other greenhouse gases) from the atmosphere. It is imperative for humanity to store a greater amount of carbon than it releases annually. The Freezing Global Warming project presents a straightforward solution through the utilisation of natural processes, photosynthesis by plants and temperature variations across the planet.

There are no requirements for the development of groundbreaking technological advancements; rather, the implementation of a straightforward concept on a global level. All nations possessing a climate conducive to biomass cultivation have the potential to contribute to a collective global resolution. This enables developed nations, which are responsible for the highest carbon emissions, to contribute a 'fair' share without resorting to politically contentious measures such as direct reparations. Additionally, the project addresses several key issues highlighted in the Intergovernmental Panel on Climate Change (IPCC) report released in March 2023 (IPCC 2023) to restore ecosystems, improve sustainable forest management, and reduce the cost of construction materials. The Freezing Global Warming proposal has the potential to provide a respite, allowing for the development and implementation of low-carbon energy sources such as commercial fusion (Mathew 2022), and carbon-free systems (Phillips et al. 2022), which are crucial for ensuring the long-term sustainability of our planet.

The expansive nature of this undertaking will result in a plethora of diverse environmental ramifications, each possessing varying degrees of significance. However, by employing thorough strategic planning and enacting suitable policies, risks can be minimised. This assertion is particularly true during the initial stage of establishing new plantations, as the implementation of suitable methods and protocols can result in significant ecological benefits in terms of soil composition and the conservation of diverse biological life, if they are carried out with careful attention. There should also be a focus on the later stages of the project and the environmental consequences related to Antarctica, as a considerable portion of these impacts could be irreversible due to the continent's pristine condition.

6 CONCLUSIONS

To avert the forthcoming climate crisis, large-scale global action is needed to reduce net emissions. The Freezing Global Warming project presents the most efficient NET or CCS solution reported-to-date. By utilising nature's efficient carbon-capture process (tree growing) and locking the captured carbon away by perpetually freezing it, a surprisingly tractable and cost-effective system can be implemented. It is worthy of note that this solution does not rely on any future invention, as all required technologies already exist and are in widespread use today.

Preprint

REFERENCES

Adhikari, S. and Ozarska, B. (2018) Minimizing environmental impacts of timber products through the production process "From Sawmill to Final Products". *Environmental Systems Research*, *7*(1), pp.1-15.

Allen, M., Antwi-Agyei, P., Aragon-Durand, F., Babiker, M., Bertoldi, P., Bind, M., Brown, S., Buckeridge, M., Camilloni, I., Cartwright, A. and Cramer, W. (2019). Technical Summary: Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change.

Antarctic and Southern Ocean Coalition (ASOC) (2022) Changing life: Sea ice. Available from: https://www.asoc.org/learn/changing-life-sea-ice/ [accessed 12 August 2023].

Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.K., Rogelj, J. and Rojas, M., (2021) Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; technical summary.

Arrhenius, S. (1896) On the influence of carbonic acid in the air upon the temperature of the ground. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science,* 41(251), pp. 237–276. Available from: https//:doi:10.1080/14786449608620846.

Austin, K., Baker, J. S., Sohngen, B. L., Wade, C. M, Daigneault, A., Ohrel, S. B., Ragnauth, S. And Bean, A. (2020) The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nature Communications,* 11(1). Available from: https://doi.org/10.1038/s41467-020-19578-z.

Azarabadi, H. and Lackner, K.S. (2019) A sorbent-focused techno-economic analysis of direct air capture. *Applied Energy,* 250, pp.959–975.

Baillie, B. (1996) Measuring the impacts of harvesting on waterways. *Report Logging Industry Research Organisation New Zealand,* 21(17). Available from: https://fgr.nz/documents/download/4428 [Accessed 30 July 2023].

Baohua, Z., Shen, H., Li, Y., Liu, Q., Jin, G., Han, J., Zhao, Y. and Pan, K. (2020) Large-scale cultivation of spirulina for biological CO_2 mitigation in open raceway ponds using purified CO_2 from a coal chemical flue gas. *Frontiers in Bioengineering and Biotechnology,*7, 441. Available from: doi:10.3389/fbioe.2019.00441.

Bayle, G. K. (2019) Ecological and social impacts of eucalyptus tree plantation on the environment. *Journal of Biodiversity Conservation and Bioresource Management*, *5*(1), pp. 93-104.

Baylin-Stern, A. and Berghout, N. (2021) Is carbon capture too expensive? Available from: https://www.iea.org/commentaries/ is-carbon-capture-too-expensive [Accessed 31 December 2022].

BBC (2023) Pioneering wind-powered cargo ship sets sail. Technology 21 August. Available from: https://www.bbc.co.uk/news/technology-66543643 [Accessed 21 August 2023].

Benson, S. M. and Orr, F. M. (2008) Carbon dioxide capture and storage, *MRS Bulletin* 33 (4), pp.303–305.

Bezerra, D.P., Oliveira, R. S., Vieira, R.S., Cavalcante,C.L. and Azevedo, D.C. (2011) Adsorption of CO_2 on nitrogen-enriched activated carbon and zeolite 13x. *Adsorption,*17, pp.235–246.

Biello, D. (2007) 10 solutions for climate change. Available from: https://www.scientificamerican.com/article/10-solutions-for-climate-change/ [Accessed 21 July 2023].

Borhani, T. N. G., Azarpour, A., Akbari, V., Alwi, S.R.W. and Manan, Z.A. (2015) CO_2 capture with potassium carbonate solutions: A state-of-the-art review. *International journal of greenhouse gas control,* 41, pp.142–162.

Brockerhoff, E. G., Jactel, H., Parrotta, J. A., Quine, C. P. and Sayer, J. (2008) Plantation forests and biodiversity: oxymoron or opportunity? *Biodiversity and Conservation*, 17, pp. 925-951.

Cabrera-Cruz, S.A., Smolinsky, J.A. & Buler, J.J. (2018) Light pollution is greatest within migration passage areas for nocturnally-migrating birds around the world. *Sci. Rep.* 8, 3261 Available from: https://doi.org/10.1038/s41598-018-21577-6.

Caitlin, T., Shannon, L. and SageStar (2018) Fruit Orchards Market Size - Global. Available from: https://askwonder.com/research/fruit-orchards-market-size-global-amhbwzlet [Accessed 20 August 2023].

Chao, C., Deng, Y., Dewil, R., Baeyens, J. and Fan, X. (2021) Post-combustion carbon capture. *Renewable & Sustainable Energy Reviews,* 138, p. 110490. Available from: https://doi.org/10.1016/j.rser.2020.110490.

Chen, H., Dong, H. Shi, Z. and SenGupta, A. (2023) “Direct air capture (DAC) and sequestration of CO_2: Dramatic effect of coordinated Cu(II) onto a chelating weak base ion exchanger,” *Science Advances*, 9(10). Available at: https://doi.org/10.1126/sciadv.adg1956.

Correa Ayram, C. A., Mendoza, M. E., Etter, A., and Salicrup, D. R. P. (2016) Habitat connectivity in biodiversity conservation: A review of recent studies and applications. *Progress in Physical Geography: Earth and Environment*, 40(1), 7–37. Available from: https://doi.org/10.1177/0309133315598713.

Danise, T., Andriuzzi, W. S., Battipaglia, G., Certini, G., Guggenberger, G., Innangi, M., Mastrolonardo, G., Niccoli, F., Pelleri, F. and Fioretto, A. (2021) Mixed-species plantation effects on soil biological and chemical quality and tree growth of a former agricultural land. *Forests*, 12 (7), 842. Available from: https://www.mdpi.com/1999-4907/12/7/842.

Delbeke, J. and Vis, P. (eds) (2019) Towards a climate-neutral Europe: curbing the trend. Routledge, London. Pp. 248. https://doi.org/10.4324/9789276082569.

Delft, CE-Delft (2023) - Shipping GHG emissions 2030: Analysis of the maximum technical abatement potential [prepared by Faber, J., van Seters, D., Scholten, P. Publication code: 23.230208.097]. Available from: https://www.transportenvironment.org/wp-content/uploads/2023/06/CE_Delft_230208_Shipping_GHG_emissions_2030_Def.pdf [Accessed 20 August 2023].

Dionco-Adetayo, E. A. (2001) Utilization of wood wastes in Nigeria: a feasibility overview. *Technovation*, 21(1), pp.55-60.

Dwyer, J. F., Schroeder, H. W. and Gobster, P. H. (1991) The significance of urban trees and forests: toward a deeper understanding of values. *Journal of Arboriculture*, 17(10), pp.276-284.

Edwards, T. L., Brandon, M. A., Durand, G., Edwards, N. R., Golledge, N. R., Holden, P. B., Nias, I. J., Payne, A. J., Ritz, C. and Wernecke, A. (2019) Revisiting Antarctic ice loss due to marine ice-cliff instability. Nature, 566(7742), pp. 58–64. https://doi.org/10.1038/s41586-019-0901-4

Preprint

EIT-Climate-KIC (no date) Friendly Fruit: growing more sustainable fruit supply chains. Available from: https://www.climate-kic.org/success-stories/friendly-fruit-sustainable-supply/ [Accessed 21 August 2023].

Environment Agency (2002) Scoping the environmental impacts of afforestation and deforestation projects. Handbook for scoping projects: environmental impact assessment. 4507 EAI B1 AW (publishing.service.gov.uk) [Accessed 24 July 2023].

Environmental Protocol | Antarctic Treaty (1991). Available at: https://www.ats.aq/e/protocol.html. [Accessed 29 August 2023].

European Environment Agency (EEA) (2023) Rail and waterborne - best for low-carbon motorised transport. Available from: https://www.eea.europa.eu/publications/rail-and-waterborne-transport [Accessed 24 July 2023].

Fenning, T. and Gershenzon, J. (2002). Where will the wood come from? Plantation forests and the role of biotechnology. *Trends in biotechnology,* 20, pp.291-6. Available from: https://doi/10.1016/S0167-7799(02)01983-2.

Food and Agriculture Organization (FAO) (no date) 5. Social Issues in Environmental Assessment, TRAINING MANUAL FOR ENVIRONMENTAL ASSESSMENT IN FORESTRY. Available from: https://www.fao.org/3/ac625e/ac625e00.htm [Accessed 29 July2023].

Forestry Commission (2023) Woodland Grants and Incentives overview table. Available from: https://www.gov.uk/government/publications/woodland-grants-and-incentives-overview-table/woodland-grants-and-incentives-overview-table [Accessed 20 August 2023].

Fretwell, P. T., LaRue, M. A., Morin, P., Kooyman, G. L., Wienecke, B., Ratcliffe, N., Fox, A. J., Fleming, A. H., Porter, C. and Trathan, P. N. (2012) "An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space," PLOS ONE, 7(4), p. e33751. Available at: https://doi.org/10.1371/journal.pone.0033751.

G.C. Institute (no date) CO_2 database. Available from: https://co2re.co/ [accessed 31 December 2022].

Gambles, I. (2019) Trees for Zero? Forestry Commission Blog 29 October. Available from: https://forestrycommission.blog.gov.uk/2019/10/29/trees-for-zero/ [Accessed 20 August 2023].

Gelles, T., Lawson, S., Rownaghi, A.A. and Rezaei, F. (2020) Recent advances in development of amine functionalized adsorbents for CO_2 capture. *Adsorption,* 26, pp.5–50.

Wikipedia (2022). Geoffrey Pyke. Available from: https://en.wikipedia.org/wiki/Geoffrey_Pyke/ [Accessed 31 December 2022].

Grant, T., Anderson, C. and Hooper, B. (2014) Comparative life cycle assessment of potassium carbonate and monoethanolamine solvents for CO_2 capture from post combustion flue gases, *International Journal of Greenhouse Gas Control,* 28, pp.35–44.

Groom, B. and Venmans, F. (2023) "The social value of offsets," *Nature*, 619(7971), pp. 768–773. Available from: https://doi.org/10.1038/s41586-023-06153-x.

Guilyardi, E., Lescarmontier, L., Matthews, R., Point, S.P., Rumjaun, A.B., Schlüpmann, J. and Wilgenbus, D. (2018) IPCC Special Report "Global Warming of 1.5 °C": Summary for Teachers.

Hani, M. and Evirgen, B. (2022) The mechanical and microstructural properties of artificially frozen Sawdust–Ice mixture (PykRetE) and its usability as a retaining structure. *International Journal of Civil Engineering*, 21(1), pp. 119–134. Available from: https://doi.org/10.1007/s40999-022-00751-y.

Holmes, J.W. (2018) Direct Air Carbon Capture and Sequestration using a Novel Biomass and Cold Storage Process. *Social Science Research Network* [Preprint]. Available from: https://doi.org/10.2139/ssrn.3365616.

Hunt, A. J., Sin, E. H., Marriott, R. and Clark, J. H. (2010) Generation, capture, and utilization of industrial carbon dioxide, *ChemSusChem: Chemistry & Sustainability Energy & Materials,* 3(3), pp.306–322.

International Panel on Climate Change (IPCC) (2005) IPCC special report on carbon dioxide capture and storage. [Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.)] Cambridge University Press, UK. pp 431.

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, Available from: https://doi.org/10.1017/9781009157896.

IPCC (2022) Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. Available from: https://doi.org/10.1017/9781009325844.

IPCC (2023) AR6 Synthesis Report: Climate Change 2023. Available from: https://www.ipcc.ch/report/sixth-assessment-report-cycle/ [Accessed 24 August 2023].

Keith, D.W., Holmes, G., Angelo, D.S. and Heidel, K. (2018) A process for capturing CO_2 from the atmosphere. *Joule* 2 (8) pp.1573–1594.

Kimberley, M., Bergin, D. and Beets, P. (2014) Carbon sequestration by planted native trees and shrubs. *Planting and managing native trees: Technical handbook Article 10.5.* Tane's Tree Trust. 12p New Zealand.

Kirby, K. and Potvin, C. (2007) Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. *Forest Ecology and Management,* 246, pp. 208-221. Available from: https://doi.org/10.1016/J.FORECO.2007.03.072.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R. A., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., 11 more authors and Woodward, F. I. (2009). Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, 2(12), pp.831-836.

Liu, C. L. C., Kuchma, O. and Krutovsky, K. V. (2018) Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Global Ecology and conservation*, 15, e00419. Available from: https://doi.org/10.1016/j.gecco.2018.e00419.

Lu, C., Bai, H., Wu, B., Su, F. and Hwang, J.F. (2008) Comparative study of CO_2 capture by carbon nanotubes, activated carbons, and zeolites. *Energy & Fuels,* 22 (5), pp.3050–3056.

Maersk (2022) Sustainability Report. Available from: https://www.maersk.com/sustainability/our-esg-priorities/climate-change [Accessed 20 August 2023].

Mathew, M.D. (2022) “Nuclear energy: A pathway towards mitigation of global warming” Progress in Nuclear Energy, 143, p. 104080. Available at: https://doi.org/10.1016/j.pnucene.2021.104080.

McQueen, N., Gomes, K.V., McCormick, C., Blumanthal, K., Pisciotta, M. and Wilcox, J. (2021) A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. *Progress in Energy,* 3(3), 032001.

Met Office (2023a) Spotlight on evidence of a warming world. *Climate News,* 49. Available from: https://content.govdelivery.com/accounts/UKMETOFFICE/bulletins/3649101 [Accessed 9 August 2023].

Met Office (2023b) Antarctic ice hits record low. Official Blog 30 June 2023. Available from: https://blog.metoffice.gov.uk/2023/06/30/antarctic-sea-ice-hits-record-low/. [Accessed 9 August 2023].

Met Office (2023c) Effects of Climate Change. Available from: https://www.metoffice.gov.uk/weather/climate-change/effects-of-climate-change [Accessed 9 August 2023].

Moura de Salles Pupo, M. and Kortlever, R. (2019) Electrolyte effects on the electrochemical reduction of CO_2, *ChemPhysChem,* 20(22), pp.2926–2935.

Nanang, D. M., Day, R. J. and Amaligo, J. N. (1997) Growth and yield of neem (*Azadirachta indica* A. Juss.) plantations in Northern Ghana. *The Commonwealth Forestry Review*, 76(2), pp.103-106.

National Academies of Sciences, Engineering, and Medicine (2019) Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. Available from: https://doi.org/10.17226/25259 [Accessed 31 December 2022].

Neeraj, and Yadav, S. (2020) Carbon storage by mineral carbonation and industrial applications of CO_2. *Materials Science for Energy Technologies,* 3, pp.494–500.

Oexmann, J., Hensel, C. and Kather, A. (2008) Post-combustion CO_2-capture from coal-fired power plants: Preliminary evaluation of an integrated chemical absorption process with piperazine-promoted potassium carbonate, *International journal of greenhouse gas control,* 2(4), pp.539–552.

Okullo, J. and Muhoro, B. (2021) Environmental and social impact assessment; Study report for the proposed commercial plantation forest on Plot LR NO; Kibwezi/Kitengei “B”/137, “B” /1512, “B” /140, “B”/141 and “B”/158 in Kitengei area, Kibwezi, Makueni County. National Environment Management Authority (NEMA). Available from: https://nema.go.ke/images/Docs/EIA_19001909/EIAEIA%201903_SR%202391%20Plantation%20Forest%20(SUBATI)%20kibwezi.pdf [Accessed 18 August 2023].

Olabi, A.G., Obaideen, K., Elsaid, K., Wilberforce,T., Sayed, E.T., Maghrabie, H.M. and Abdelkareem, M.A. (2022) “Assessment of the pre-combustion carbon capture contribution into sustainable development goals SDGs using novel indicators,” *Renewable & Sustainable Energy Reviews*, 153, p. 111710. Available from: https://doi.org/10.1016/j.rser.2021.111710.

Pant, D., Shah,K.K., Sharma,S., Bhatta,M., Tripathi, S., Pandey, H., Tiwari, H., Shrestha,J., Bhat A.K. (2023) Soil and Ocean Carbon Sequestration, Carbon Capture, Utilization, and Storage as Negative Emission Strategies for Global Climate Change. *J Soil Sci Plant Nutr* **23**, pp.1421–1437. Available from: https://doi.org/10.1007/s42729-023-01215-5.

Phillips, N., Draper, T.C., Richard Mayne, R., Reynolds, D.M. and Adamatzky, A. (2022) Marimo actuated rover systems. *Journal of Biological Engineering*, 16(1). Available from: https://doi.org/10.1186/s13036-021-00279-0.

Renfrew, S.E., Starr, D.E. and Strasser, P. (2020) Electrochemical approaches toward CO_2 capture and concentration. *ACS catalysis,* 10(21), pp.13058–13074.

Reuters (2023) US 'under no circumstances' will pay climate reparations, Kerry says. 13 July 2023. Available from: https://www.reuters.com/world/us/us-under-no-circumstances-will-pay-into-loss-damage-fund-kerry-2023-07-13/ [Accessed 24 August 2023].

Sabatino, F., Grimm, A., Gallucci, F., van Sint Annaland, M., Kramer, G.J. and Gazzani, M. (2021) A comparative energy and costs assessment and optimization for direct air capture technologies. *Joule*, 5(8), pp.2047-2076.

Shah, N. W., Baillie, B. R., Bishop, K., Ferraz, S., Högbom, L. and Nettles, J. (2022) The effects of forest management on water quality. *Forest Ecology and Management*, 522, Available from: https://doi.org/10.1016/j.foreco.2022.120397.

Sharma, P., Kaur, A., Batish, D. R., Kaur, S., and Chauhan, B. S. (2022) Critical insights into the ecological and invasive attributes of *Leucaena leucocephala*, a tropical agroforestry species. *Frontiers in Agronomy*, 4. 890992. Available from: https://doi.org/10.3389/fagro.2022.890992.

Shi, X., Xiao, H., Azarabadi, H., Song, J., Wu, J., Chen, X. and Lackner, K.S. (2020) Sorbents for the direct capture of CO_2 from ambient air. *Angewandte Chemie International,* 59(18), pp.6984–7006.

Smith, P., House, J.I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P.C., Clark, J.M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., McDowell, R., Griffiths, R.I., .Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J. and Pugh, T.A. (2016) Global change pressures on soils from land use and management. *Glob Chang Biol*. 22(3), pp.1008-28.

Snæbjörnsdóttir, S. Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S.R. and Oelkers, E.H. (2020) Carbon dioxide storage through mineral carbonation. *Nature Reviews Earth & Environment,* 1(2), pp.90–102.

Solakivi, T., Kiiski, T. and Ojala, L. (2018) The impact of ice class on the economics of wet and dry bulk shipping in the Arctic waters. *Maritime Policy & Management*, 45(4), pp. 530–542. Available from: https://doi.org/10.1080/03088839.2018.1443226.

Sordello, R., Ratel, O., Flamerie De Lachapelle, F., Leger, C., Dambry , A. and Vanpeene, S. (2020) Evidence of the impact of noise pollution on biodiversity: a systematic map. *Environ Evid* 9, 20 Available from: https://doi.org/10.1186/s13750-020-00202-y.

Sullivan, I., Goryachev, A., Digdaya, I.A., Li, X., Atwater, H.A., Vermaas, D.A. and Xiang, C. (2021) Coupling electrochemical CO_2 conversion with CO_2 capture. *Nature Catalysis,* 4(11), pp.952–958.

The turning point | Deloitte" (2022) Deloitte [Preprint]. Available at: https://www.deloitte.com/global/en/issues/climate/global-turning-point.html [Accessed 12 Sept 2023].

The World Bank (1991) Environmental assessment sourcebook: volume 2 - sectoral guidelines (English). World Bank technical paper, no. WTP 140 Washington DC; World Bank. Available from: http://documents.worldbank.org/curated/en/415971468137388990/Environmental-assessment-sourcebook-volume-2-sectoral-guidelines [Accessed 20 July 2023].

Thonemann, N., Zacharopoulos, L., Fromme, F. and Nühlen, J. (2022) Environmental impacts of carbon capture and utilization by mineral carbonation: A systematic literature review and meta life cycle assessment. *Journal of Cleaner Production,* 332, 130067. Available from: https://doi.org/10.1016/j.jclepro.2021.130067.

Tripathi, N., Hills, C. D., Singh, R. S. and Atkinson, C. J. (2019) Biomass waste utilisation in low-carbon products: harnessing a major potential resource. *Npj Climate and Atmospheric Science*, 2(1), 35. Available from: https://doi.org/10.1038/s41612-019-0093-5.

UN Environment Programme (UNEP) (2020) UNEP and the climate emergency. Briefing paper for the 75th session of the United Nations General Assembly. September 2020. Available from: https://www.unep.org/unep-and-climate-emergency [Accessed 24 August 2023].

United Nations (2023a) Secretary-General's opening remarks at press conference on climate [Press release] 27 July. Available from: https://www.un.org/sg/en/content/sg/speeches/2023-07-27/secretary-generals-opening-remarks-press-conference-climate. [Accessed 15 August 2023].

United Nations (2023b) Sustainable Development. Available from: https://sdgs.un.org/ [Accessed 9 August 2023].

United Nations (no date a) The Kyoto Protocol. Available from: https://unfccc.int/process-and-meetings/the-kyoto-protocol/history-of-the-kyoto-protocol/text-of-the-kyoto-protocol [Accessed 24 August 2023].

United Nations (no date b) Marking the Kyoto Protocol's 25th anniversary | United Nations. Available from: https://www.un.org/en/climatechange/marking-kyoto-protocol%E2%80%99s-25th-anniversary [Accessed 29 August 2023].

United Nations (no date c) The Paris Agreement. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement [Accessed 24 August 2023].

United Nations (no date d) COP27 Delivering for People and the Planet. Available from: https://www.un.org/en/climatechange/cop27 [Accessed 24 August 2023].

Vanbeveren, S. P. and Ceulemans, R. (2019) Biodiversity in short-rotation coppice. *Renewable and Sustainable Energy Reviews*, 111, pp.34-43.

Varghese, A. M. and Karanikolos, G.N. (2020) CO_2 capture adsorbents functionalized by amine–bearing polymers: A review. *International Journal of Greenhouse Gas Control,* 96, 103005.

Wang, C., Zhang, W., Li, X. and Wu, J. (2022) A global meta-analysis of the impacts of tree plantations on biodiversity. *Global Ecology and Biogeography*, 31(3), pp. 576-587.

Wang, J., Pu, Q., Ning, P. and Lu, S. (2021) Activated carbon-based composites for capturing CO_2: a review. *Greenhouse Gases: Science and Technology,* 11(2) pp.377–393.

Wildenborg,T., Gale,J., Hendriks,C., Holloway,S., Brandsma,R., Kreft,E. and Lokhorst, A, (2005) Cost curves for CO2 storage: European sector, In : Rubin, E.S., Keith, D.W., Gilboy, C.F., Wilson, M., Morris, T., Gale, J. and Thambimuthu, K. (Eds.) (2005) Greenhouse Gas Control Technologies 7, pp.603-610. Elsevier Science Ltd.

Woodland Trust (2023) What Urban Trees do for us. Available from: https://www.woodlandtrust.org.uk/protecting-trees-and-woods/benefits-of-urban-trees/ [Accessed 20 August 2023].

Woolf, D., Amonette, J., Street-Perrott, F., Lehmann, J. and Joseph S. (2010) Sustainable biochar to mitigate global climate change. *Nat Commun* 1 (56). Available from:

https://doi.org/10.1038/ncomms1053 [https://doi.org/10.1038/ncomms1053 Accessed 15 August 2023].

World Resources Institute (2023) Global Forest Review: Production Forests. Available from: https://research.wri.org/gfr/forest-designation-indicators/production-forests [Accessed 21 August 2023].

Wood Recyclers Association (2023) Available from: https://woodrecyclers.org/ [Accessed 20 August 2023].

Xiu, S. and Shahbazi, A. (2012) Bio-oil production and upgrading research: A review. *Renewable & Sustainable Energy Reviews*, 16(7), pp. 4406–4414. Available from: https://doi.org/10.1016/j.rser.2012.04.028.

Yadav, S. and Mondal, S. (2022) "A review on the progress and prospects of oxy-fuel carbon capture and sequestration (CCS) technology," *Fuel*, 308, p. 122057. Available from: https://doi.org/10.1016/j.fuel.2021.122057.

Younger, J. L., Clucas, G. V., Kooyman, G., Wienecke, B., Rogers, A. D., Trathan, P. N., Hart, T. and Miller, K. J. (2015) Too much of a good thing: sea ice extent may have forced emperor penguins into refugia during the last glacial maximum. *Global Change Biology*, 21(6), pp.2215-2226.

Zarafshar, M., Bazot, S., Matinizadeh, M., Bordbar, S. K., Rousta, M. J., Kooch, Y., Enayati, K., Abbasi, A, and Negahdarsaber, M. (2020) Do tree plantations or cultivated fields have the same ability to maintain soil quality as natural forests? *Applied Soil Ecology*, 151, 103536. Available from: https://doi.org/10.1016/j.apsoil.2020.103536.

Zeng, N. (2008) "Carbon sequestration via wood burial," *Carbon Balance and Management*, 3(1). Available from: https://doi.org/10.1186/1750-0680-3-1.

Zhou, X., Wen, Y., Goodale, U. M., Zuo, H., Zhu, H., Li, X., You, Y., Yan, L., Su, Y. and Huang, X. (2017) Optimal rotation length for carbon sequestration in Eucalyptus plantations in subtropical China. *New Forests*, 48, 609-627.

Authors Biography

Neil Phillips has 20 years of expertise in the implementation of unconventional bioengineering solutions. Co-PI on Horizon 2020 project to commercialise biosensing platform for environmental monitoring. He has worked on the design and manufacture of bioreactors.

Sarah M. Ayling is a plant physiologist with over 40 years of experience. She has studied the impact of environmental conditions on plants, including trees, in the UK, US, and Australia.

Norman M. Ratcliffe has over 30 years of experience in gas/volatile analysis research, specialising in agrifood. He created the first volatile organic compound (VOC) quality control system for storing vegetables.

Ben de Lacy Costello has over 25 years of experience in gas analysis, including production of gas sensors and sensor array systems for volatile detection. He works on projects with sustainable air travel and sustainable farming, where he measures and reduces methane emissions.

William Foord is an MSc environmental management student currently studying at the University of the West of England, with an undergraduate degree in physical geography from the University of Portsmouth, UK.

Thomas C. Draper is a chemist with a wide range of expertise, from nanotechnology to molecular biology to molecular computing. He has over 10 years of experience working on diverse research projects.

Anthony Plumridge is an economist with experience in cost-benefit analyse and a background in social return on investment and carbon accounting. He has expertise in predicting the worldwide economic consequences associated with project implementation.

Jona Razzaque is an expert on environmental laws and policies. She serves as a member of the IUCN World Commission on Environmental Law.